The Physics Landscape

Chris Quigg
Fermi National Accelerator Laboratory

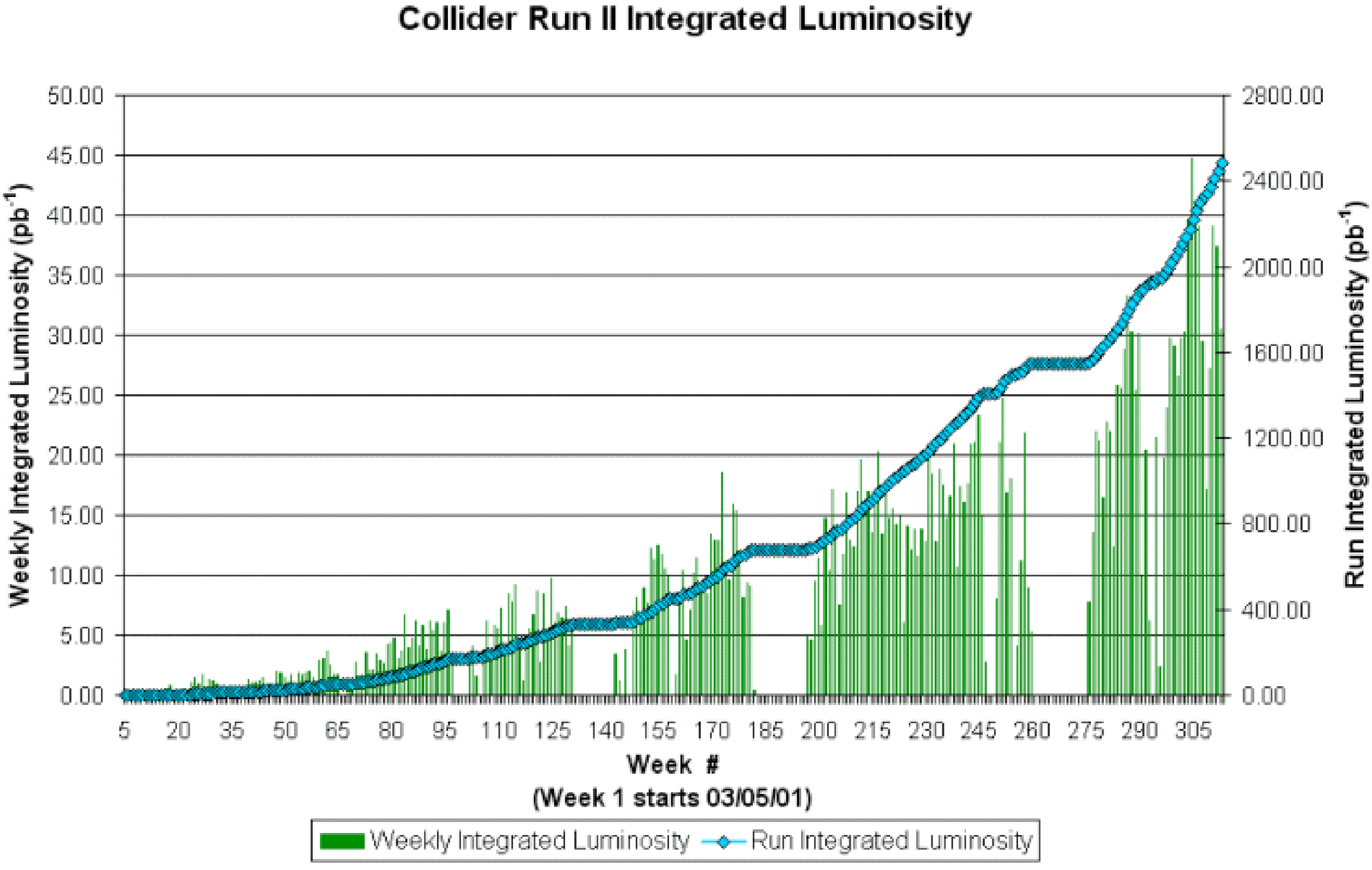
Fermilab ILC Symposium · 7 March 2007

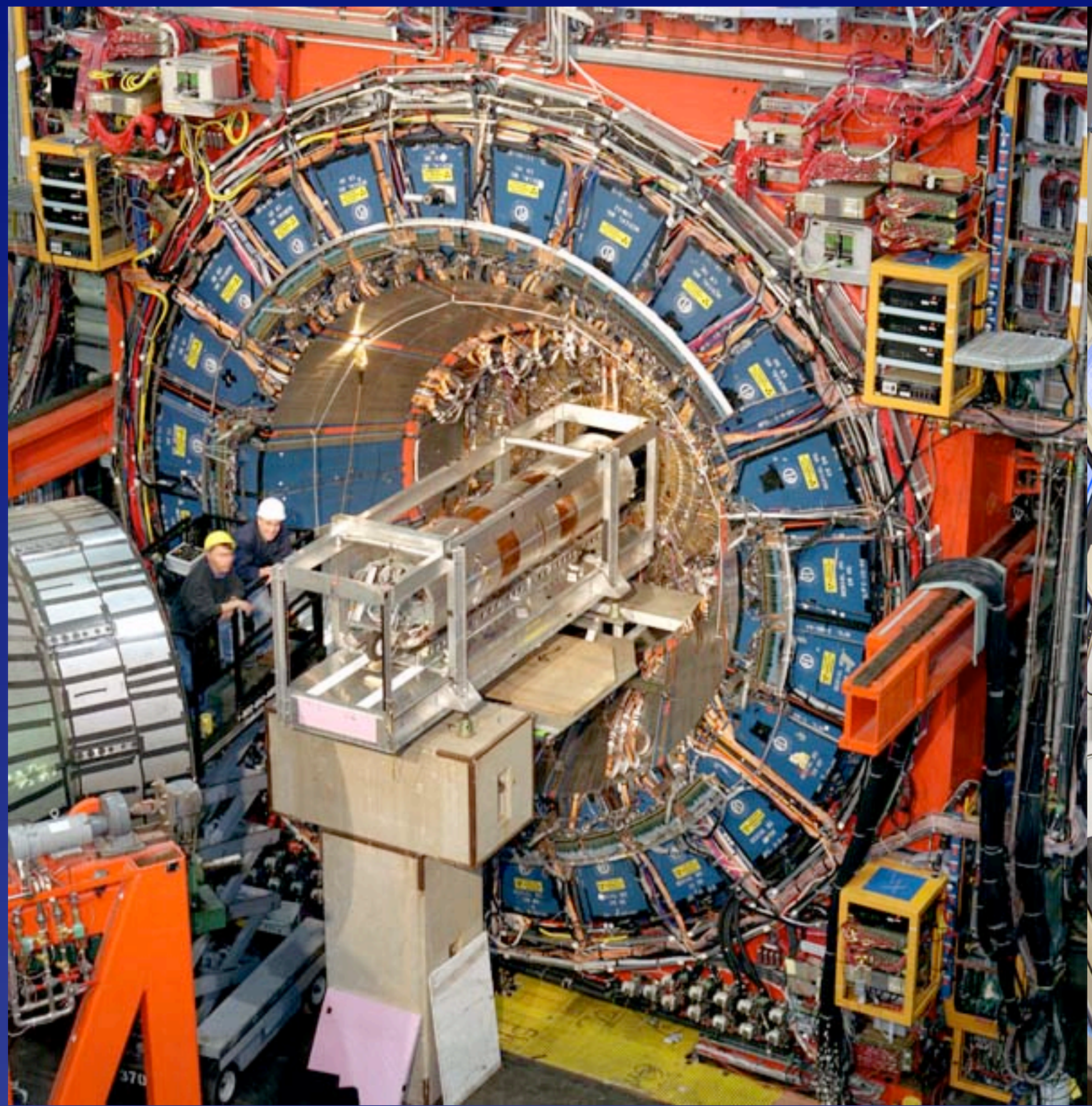
A Decade of Discovery Past

- ▷ Electroweak theory $\longrightarrow$ law of nature [Z, e^+e^-, $\bar{p}p$, νN, $(g-2)_\mu$, ...]
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ? ▷ Neutrino flavor oscillations: $\nu_\mu \longrightarrow \nu_\tau$, $\nu_e \longrightarrow \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}]
- ▷ Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- ? ▷ Discovery of top quark [$\bar{p}p$]
- ? ▷ Direct CP violation in $K \longrightarrow \pi\pi$ decay [fixed-target]
- ? ▷ B-meson decays violate CP [$e^+e^- \longrightarrow B\bar{B}$]
- ? ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

2

Tevatron Collider is breaking new ground in sensitivity

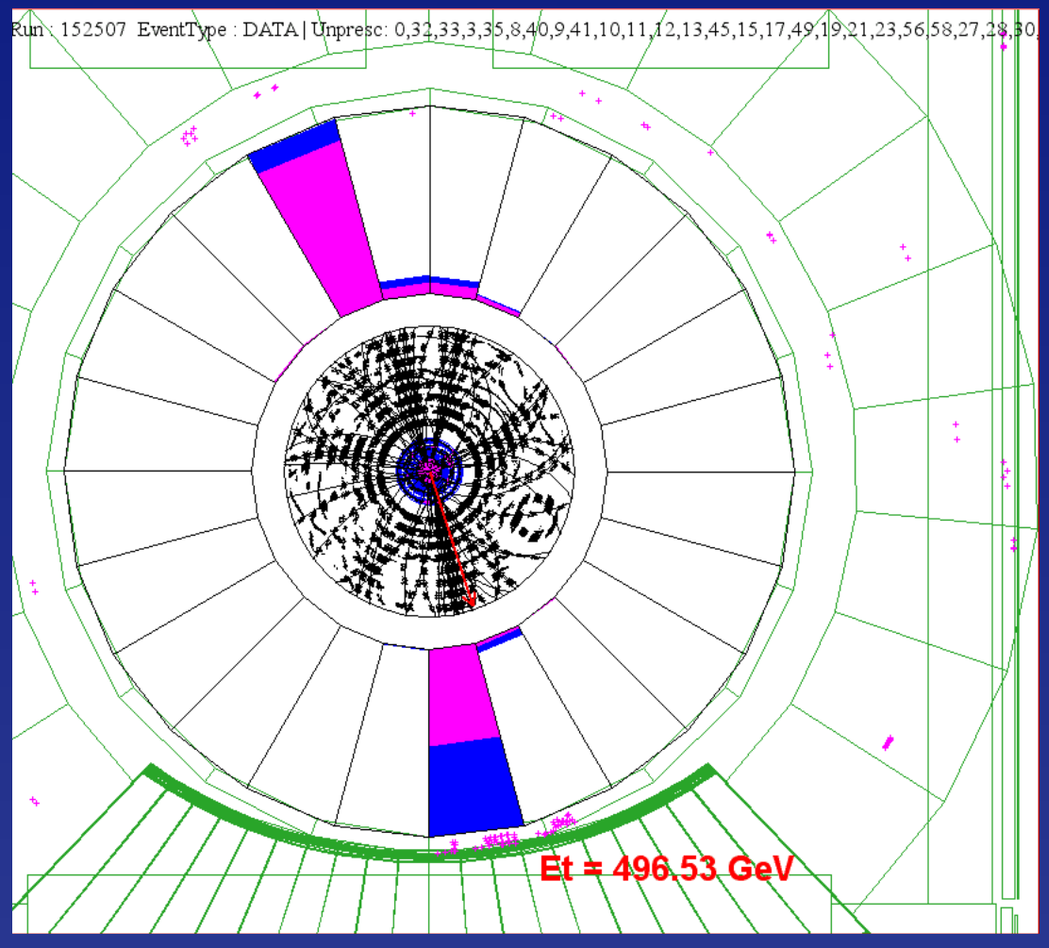

Collider Run II Integrated Luminosity
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
2800.00
2400.00
2000.00
1600.00
1200.00
800.00
400.00
0.00
5 20 35 50 65 80 95 110 125 140 155 170 185 200 215 230 245 260 275 290 305
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

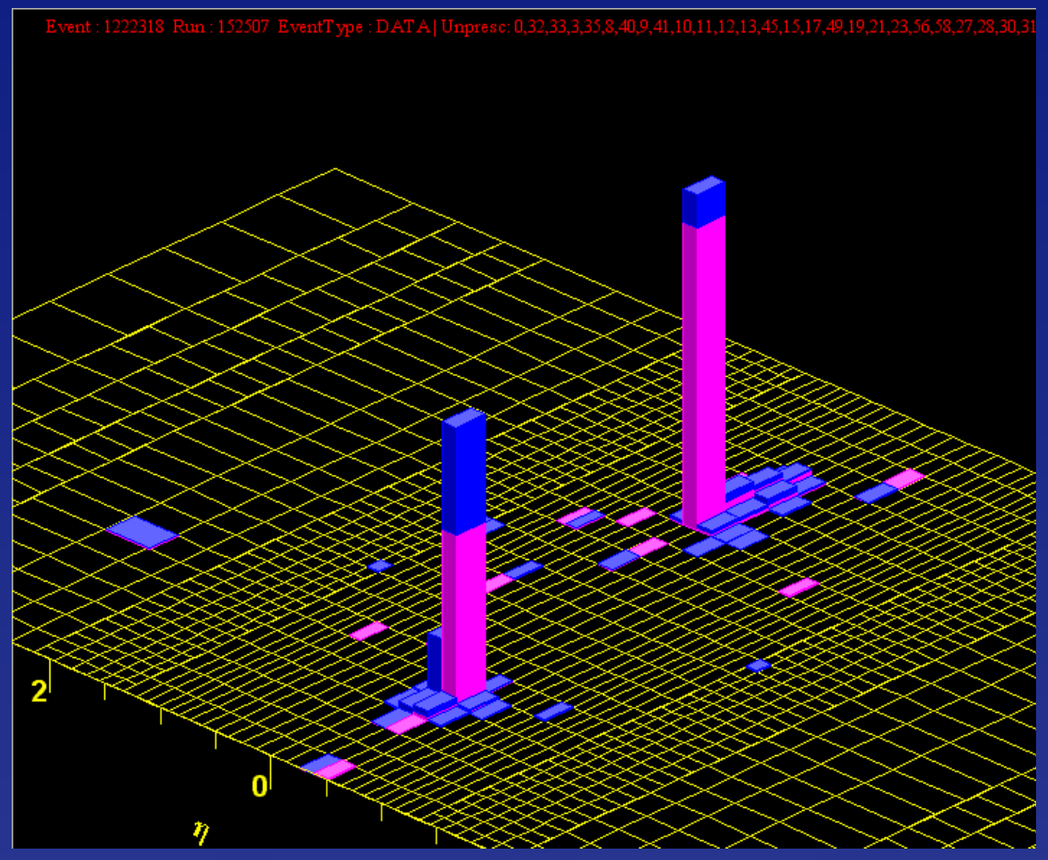


5

The World's Most Powerful Microscopes

nanonanophysics





CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $\boxed{q\bar{q} \to \text{jet} + \text{jet}}$

6


DØ tt̄ event

Particle accelerators are time machines …

Not to replicate the early universe,
but to create conditions
that allow us to discover

something of the laws that prevailed
when the universe was smaller & hotter.

(now back to 1 picosecond)

8

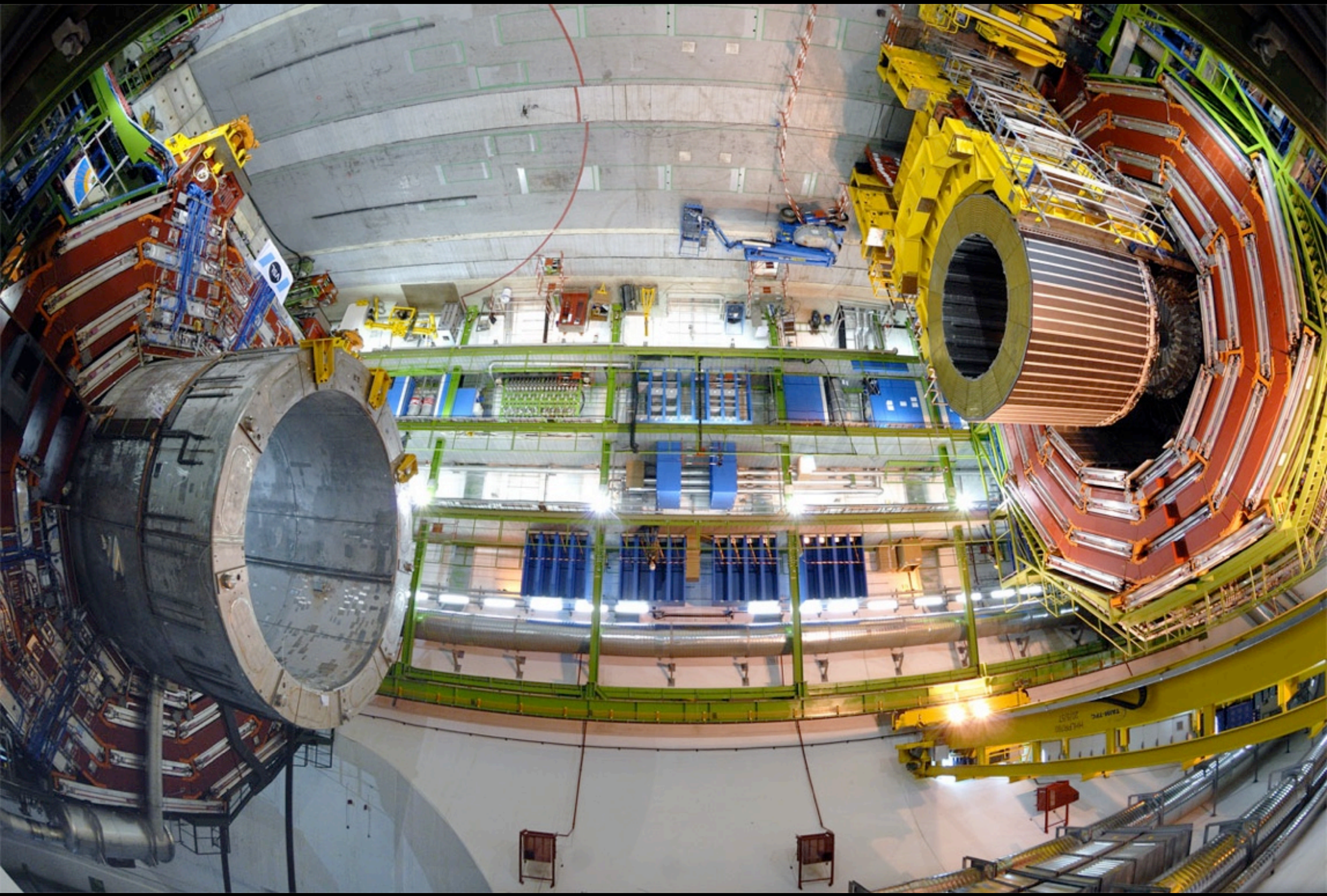
LHC will operate soon, breaking new ground in E & *L*

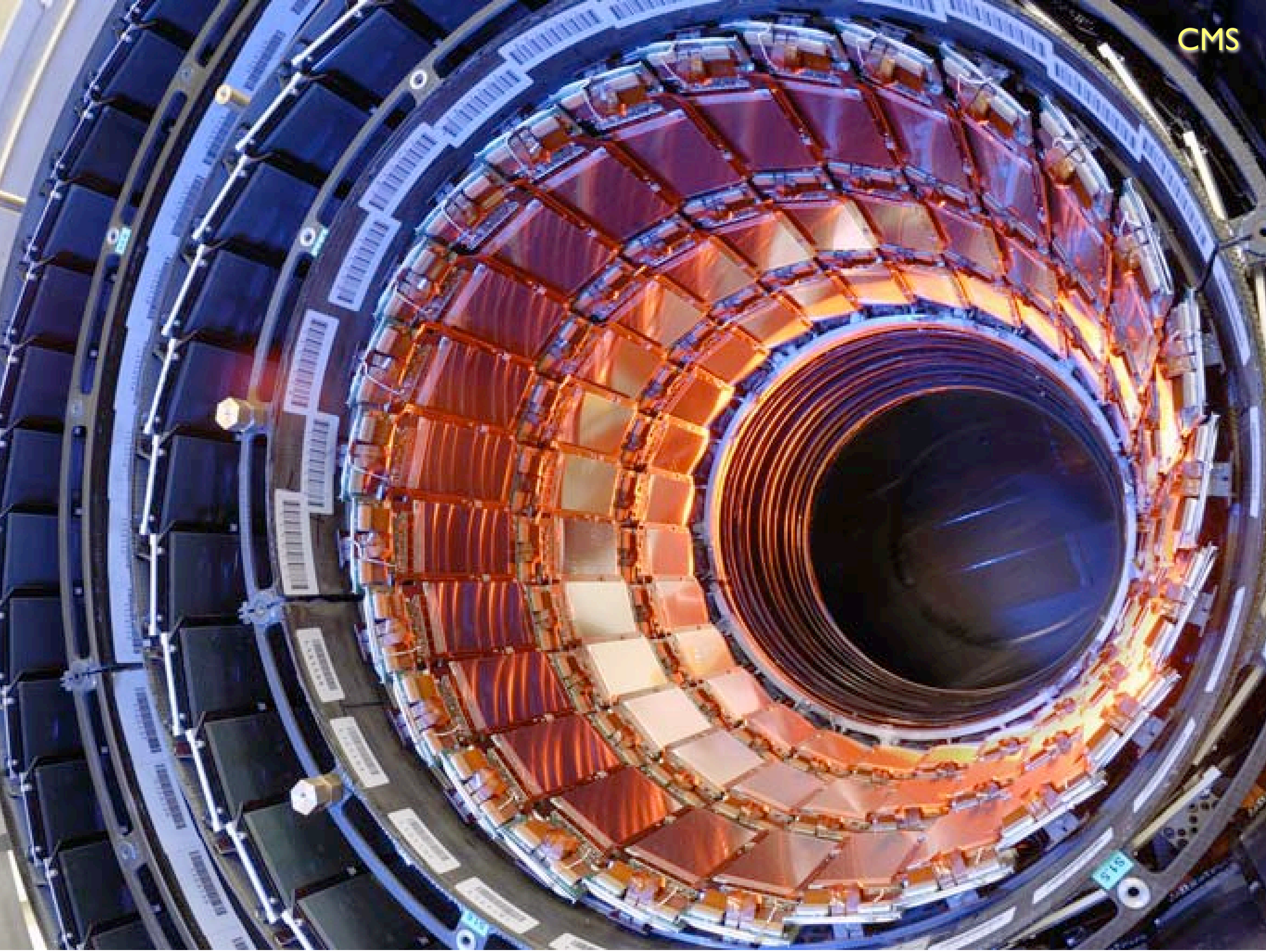
CMS

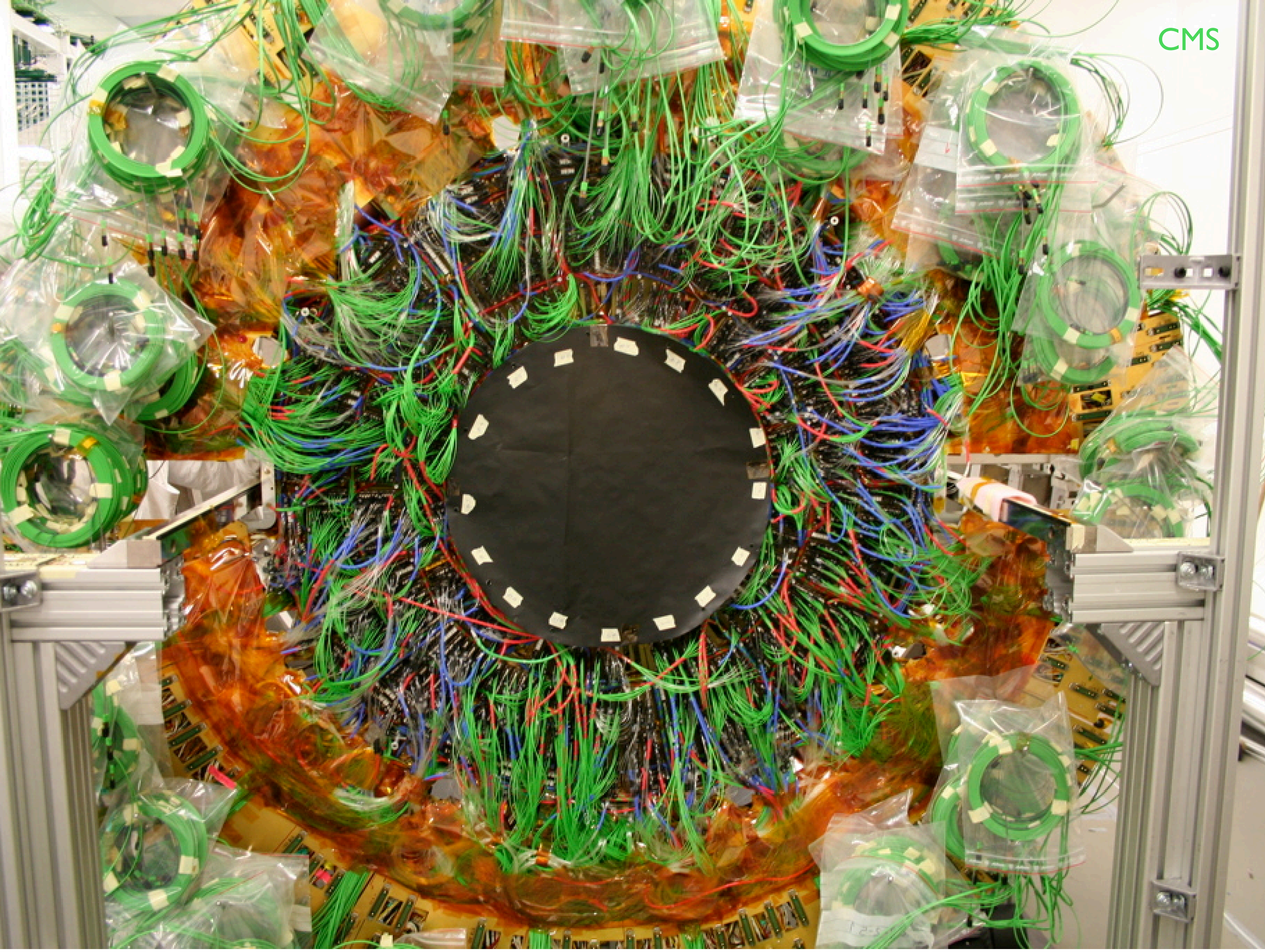
CMS

CMS

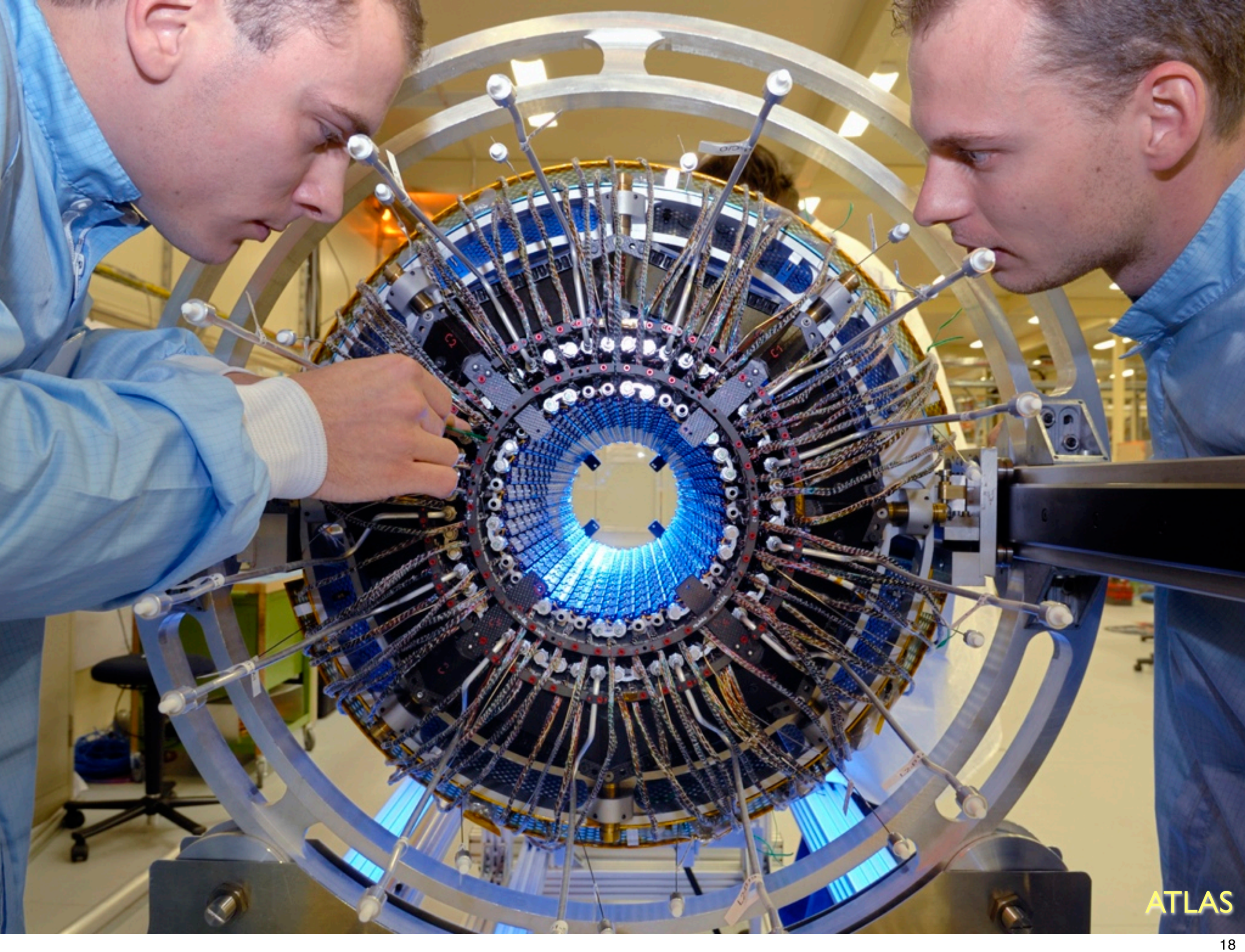
14




CMS


CMS

ATLAS


ATLAS

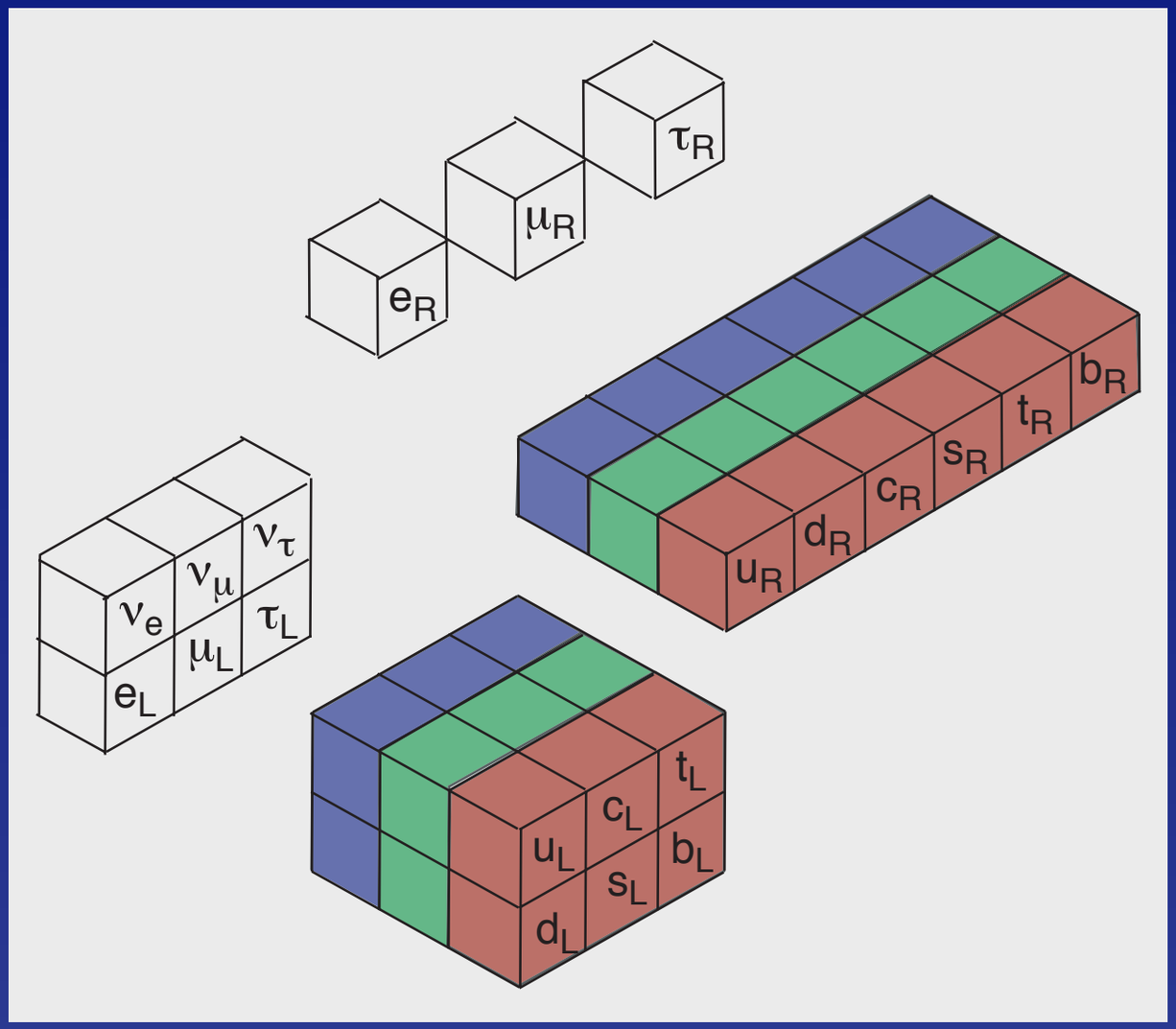
ILC is on the drawing board, with a value estimate

TABLE 2.1-1
Global Accelerator Parameters for 500 GeV cms.

Center-of-mass energy	500 GeV
Peak luminosity	2×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Availability	75%
Repetition rate	5 Hz
Duty cycle	0.005%
Main linacs	
Average accelerating gradient in cavities	31.5 MV/m
Length of each main linac	11 km
Beam pulse length	1 ms
Average beam current in pulse	9.0 mA
Damping rings	
Beam energy	5 GeV
Circumference	6.7 km
Length of beam delivery section (2 beams)	4.5 km
Total site length	31 km
Total site power consumption	230 MW
Total installed power	~300 MW

Our Picture of Matter (the revolution just past)

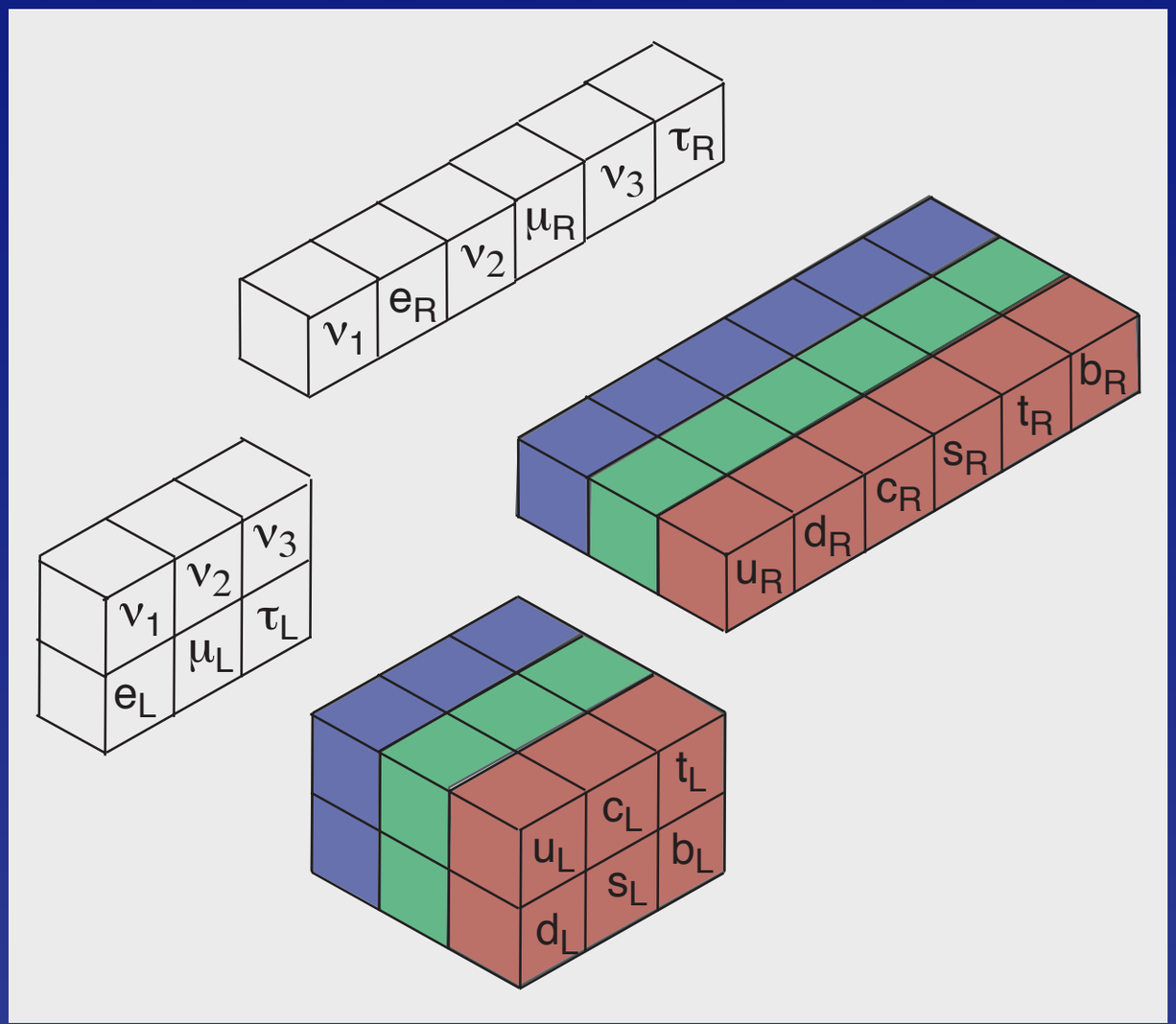
Pointlike ($r \leq 10^{-18}$ m) quarks and leptons



Strong, Weak, Electromagnetic Interactions:
$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

Our Picture of Matter (the revolution just past)

Pointlike ($r \leq 10^{-18}$ m) quarks and leptons



Strong, Weak, Electromagnetic Interactions:
$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$ gauge symmetries

New Physics on the Fermi Scale

Thought experiment (1977): *WW* scattering

Electroweak theory makes sense if

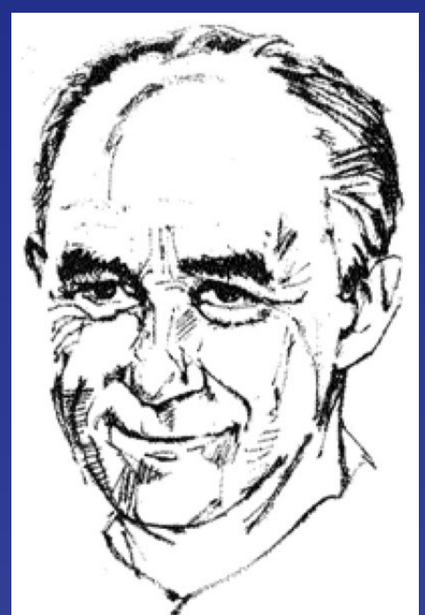
something happens

at energies around 1 TeV

Either the Higgs boson

Or strong *WW* scattering

Tipping point: $M_{Higgs} < \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2}$

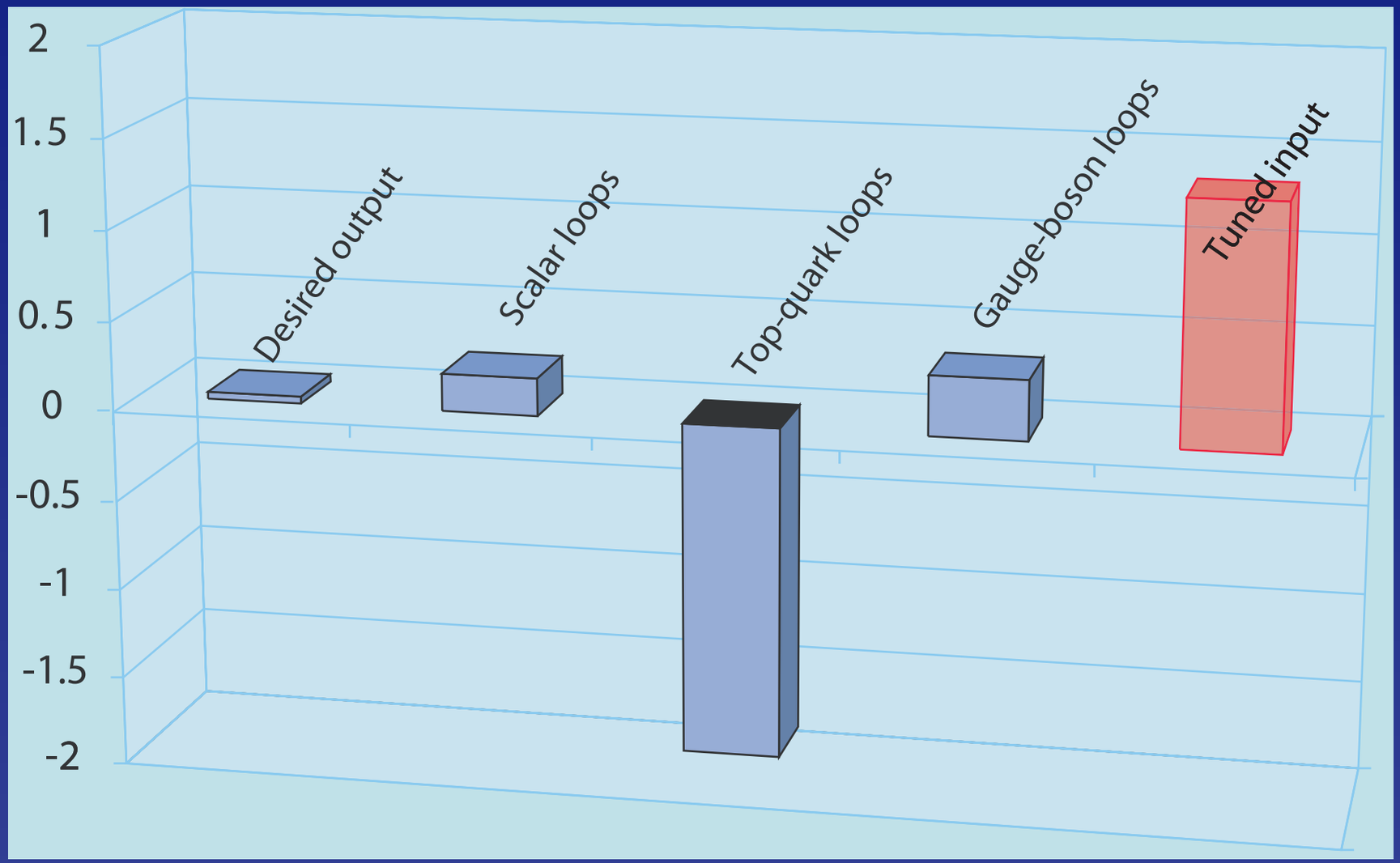


22

More New Physics on the Fermi Scale?

Does M_H < 1 TeV make sense?

The peril of quantum corrections – hierarchy problem



5 TeV

23

More New Physics on the Fermi Scale?

Does $M_H < 1$ TeV make sense?

The peril of quantum corrections – hierarchy problem

Responses: extend electroweak theory

Supersymmetry

Technicolor

Extra spacetime dimensions

"Little Higgs" models

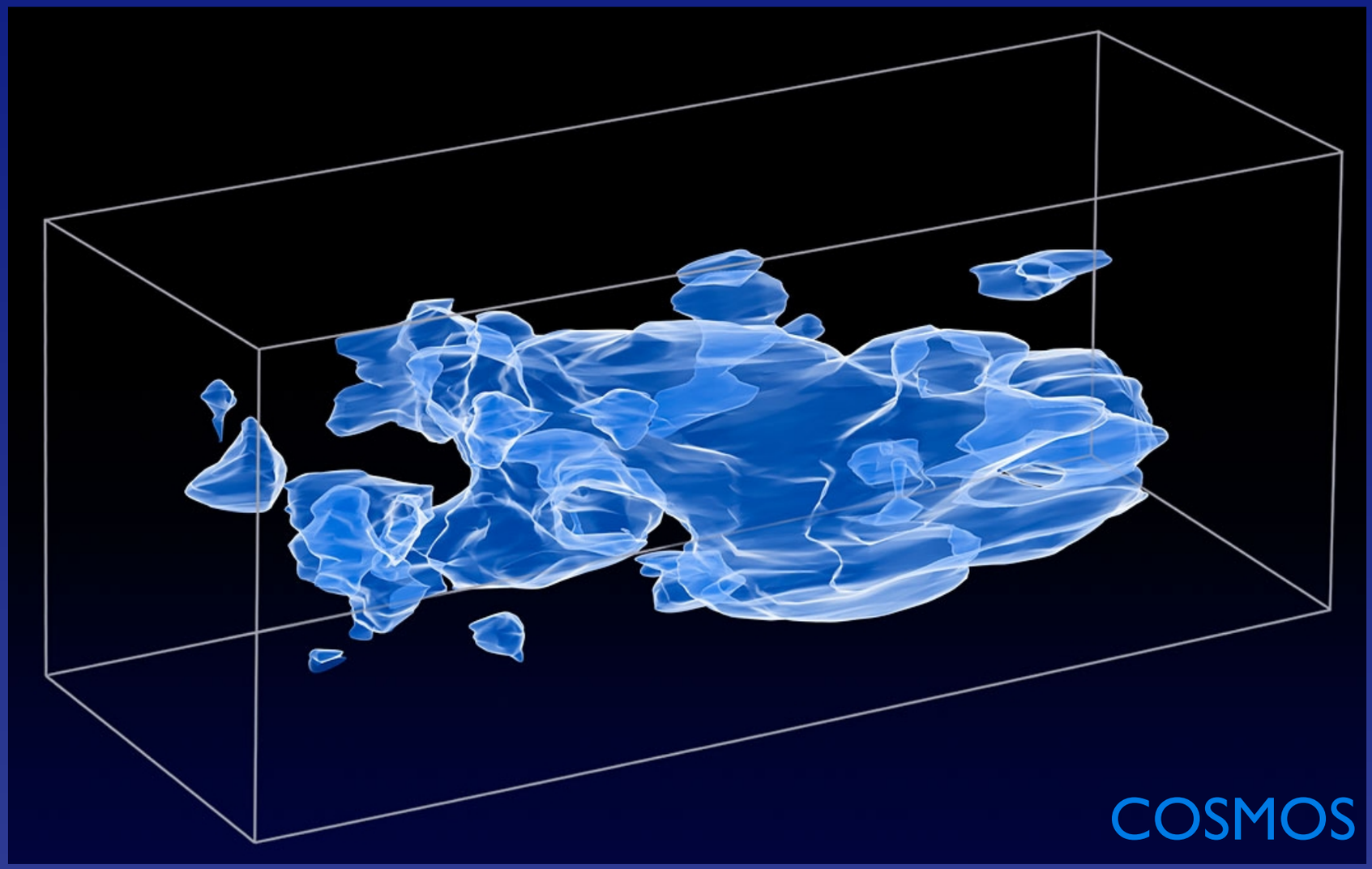
Bring new physics down to 1 TeV

Opinion: Fermi scale holds Higgs boson + other new physics

24

More New Physics on the Fermi Scale?

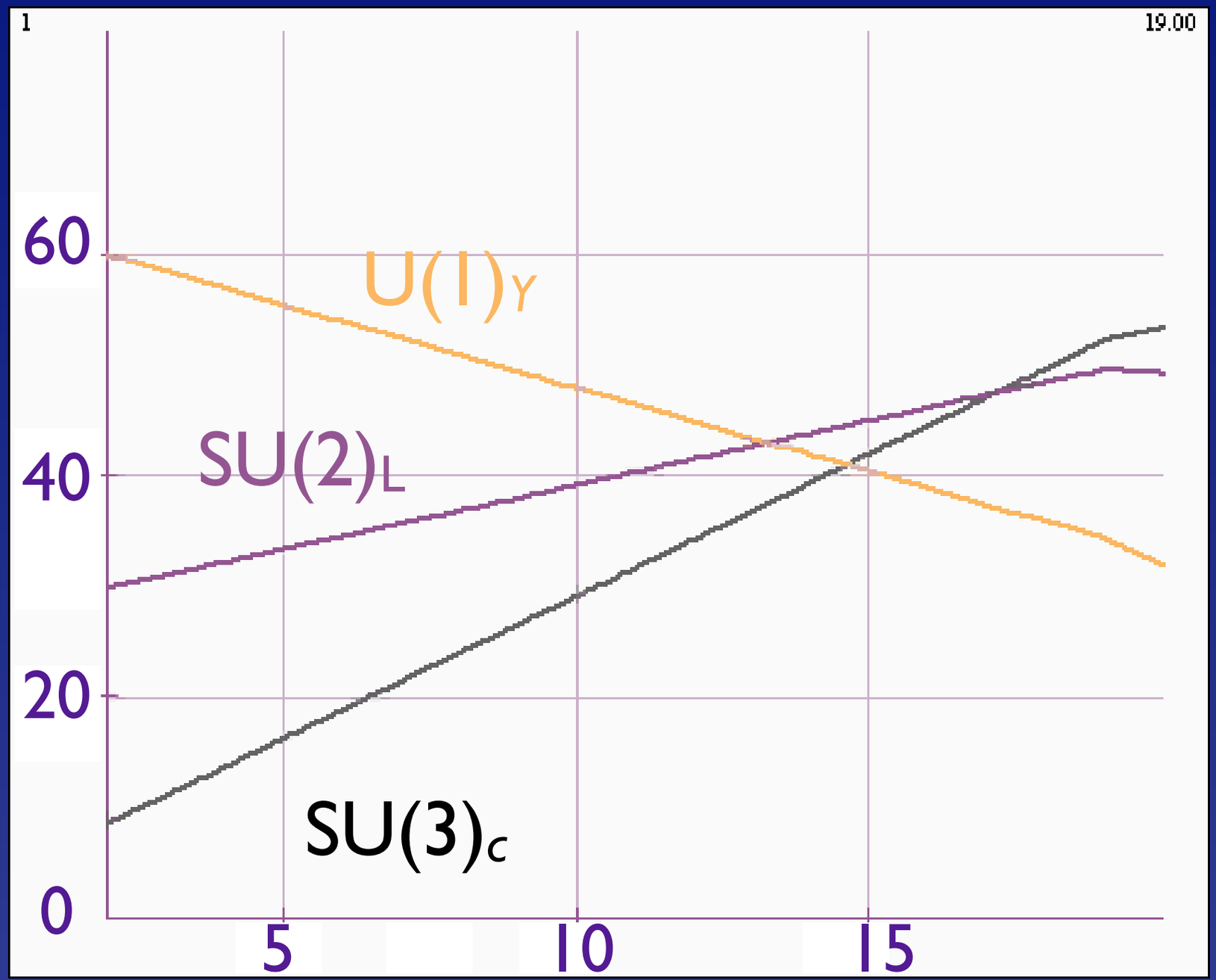
If dark matter interacts weakly …



… its likely mass is 0.1 to 1 TeV: *Fermi scale*

25

Fermi scale + supersymmetry : unification?



Imagine a world without a Higgs mechanism

27

If electroweak symmetry were not hidden . . .

▷ Quarks and leptons would remain massless

▷ QCD would confine them into color-singlet hadrons

▷ *Nucleon mass would be little changed,*

▷ QCD breaks EW symmetry, gives ($1/2500\times$observed) masses to W, Z, so weak-isospin force doesn't confine

▷ Proton outweighs neutron: rapid β-decay $\Rightarrow$ lightest nucleus is one neutron; no hydrogen atom

▷ (?) some light elements in BBN, but ∞ Bohr radius

▷ No atoms (as we know them) means no chemistry, no stable composite structures like solids, liquids we know

. . . the character of the physical world would be profoundly changed

28

Searching for the mechanism of electroweak symmetry breaking, we seek to understand

why the world is the way it is.

This is one of the deepest questions humans have ever pursued, and

it is coming within the reach of particle physics.

29

Essential step toward understanding the new force that shapes our world:
Find the Higgs boson and explore its properties.

- ✳ Is it there? How many?
- ✳ Verify quantum numbers (spin, parity, …)
- ✳ Does *H* generate mass for gauge bosons and for fermions?
- ✳ How does *H* interact with itself?

Linear collider an ideal tool: $e^+e^- \to HZ$

30

The Meaning of Identity

What makes a top quark a top quark,
an electron an electron, a neutrino a neutrino?

- What sets masses, mixings of quarks & leptons?
- What is the subtle difference between matter and antimatter telling us?
- Neutrino oscillations give another take: possible insight into matter excess in universe

All fermion masses mean new physics

- Will new kinds of matter help us see pattern?

Fermi-scale discoveries have implications for flavor physics

31

The Unity of Quarks and Leptons

- What do quarks and leptons have in common?
- Why are atoms so remarkably neutral?
- Which quarks go with which leptons?

- Quark-lepton extended family: proton decay
- Unified theories: coupling constant unification
- Rational mass pattern at high energies?

Project from Fermi scale to higher energies

32

A New Conception of Spacetime?

- Could there be more space dimensions than we have perceived?
- What is their size? their shape?
- How do they influence the world?
- How can we map them?

Key to understanding why gravity is so weak?

33

A chronic dull headache for thirty years

Why is empty space so nearly massless?

Higgs field fills all of space with energy density $>10^{24}$ g/cc

But empty space weighs next to nothing: $< 10^{-29}$ g/cc

Accelerating expansion of universe:
vacuum energy is present
… recasts problem

34

Connections

35

Building the scientific case

Motivation for a linear collider to explore the Fermi scale is general and strong:

Benefit of multiple views of the rich new terrain: Telescope analogy

Discoveries at the Tevatron or at the Large Hadron Collider can test ILC parameter choices and make the case for the ILC specific and compelling.

How would you use the ILC?

?